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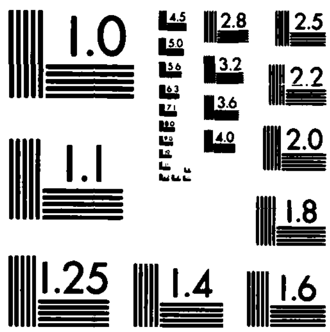

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A complete descripton of the Poseidon electron beam generator is presented.

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THE POSEIDON ELECTRON BEAM GENERATOR

INTRODUCTION

The POSEIDON electron beam generator was designed to perform a series of experiments to produce a closed field line plasma confinement system with two rotating relativistic electron beams. Previous experimental studies[1] have shown that a single rotating beam (generated by the TRITON electron beam generator[2]) can produce a plasma in a reversed field configuration inside an initially field free metal tube. The magnetic fields were maintained with induced plasma currents rather than the beam electrons themselves. However, because the beam was injected from one end of the system, a net axial current persisted which precluded axial containment. To eliminate this current, it was proposed[3] to inject a second rotating beam from the opposite end of the system.

The basic parameters of POSEIDON, as dictated by its initial application, are: a current in excess of 140 kA, an impedance between 5 and 10 ohms, and a pulse length of 100 nsec. Nevertheless, the design is sufficiently flexible to allow other experimental work involving electron beams. In addition, the generator can also be used as a pulsed power source, for example, a nanosecond rise time current drive for a high density *z*-discharge.

Because POSEIDON will be used for a series of physics experiments, a relatively high repetition rate and a high degree of reliability were required. Thus the underlying design philosophy was conservative: Mechanical and electrical stresses were kept well below normal limits and the basic design follows closely that of the proven TRITON generator, thus minimizing electrical surprises. Emphasis was placed on ease of maintenance and operation, ready access to all major components, use of existing or readily fabricated parts (e.g., Gamble II type capacitors, simple Copper Sulfate resistors), and, of course, low cost.

GENERAL DESCRIPTION

POSEIDON consists of an oil insulated Marx generator that charges, through a set of pressurized nitrogen switches, a water dielectric Blumlein line (hereinafter referred to in the corrupted, but normally accepted term, Blumlein). The Blumlein is shorted at one end with a single-channel water-insulated switch, while prepulse is suppressed with an oil-insulated single-channel switch between the inner conductor and diode. The vacuum insulated planar lucite diaphragm diode uses a field emission cathode, which can easily be changed to accommodate the experiment. Presently the anode is a thin foil made of various materials (aluminized mylar, capton, titanium and aluminum have all proven successful) and is changed after each shot by a specially designed anode foil changer.[4] However, in principle, the diode can be easily converted to a foilless diode or even a coaxial high power line driver.

The design parameters of POSEIDON are listed in Table I. A line drawing and photograph of the generator appear in Figs. 1 and 2, and each component is discussed in detail in the remainder of this monograph.

Manuscript submitted June 7, 1982.

MARX TANK

The 8000 gallon Marx tank (Fig. 3) is of double wall construction and is designed to be leakproof, over-fill proof, moveable, and comply with all EPA and OSHA regulations. The tank walls are penetrated below the oil fill level only by the main flange for the Blumlein and the fill pipe for the prepulse switch. A platform with railing runs along the length of the tank to allow safe visual inspection of the Marx. Inside the tank a grated flooring provides sure footing in the presence of residual oil and a moveable adjustable height dolly mounted on rails eliminates lower back injuries during capacitor removal. The entire tank, as well as the attached Blumlein, is mounted on low friction bearings gliding on hardened steel rails. As a result, the generator can be moved by one hand winch, even when fully laden with oil and water.

MARX CIRCUIT

POSEIDON uses a 24 stage Marx (see Figs. 4 and 5) with each stage containing two Aerovox .5 μf 100 kV capacitors connected in series. This arrangement results in an erected Marx capacitance identical to that of TRITON (12 stages, .5 μf per stage), allowing the electrical characteristics of the Blumlein to be patterned after that of TRITON, even though the stored energy is four times greater. In addition, as the capacitors are the same as employed in TRITON and the NRL Gamble accelerators, an ample supply of spares is on hand. The capacitors are hung by nylon straps from two overhead pipes. A photograph taken inside the Marx is shown in Fig. 6.

The Marx uses $N = 4$ coupling to achieve maximum over-voltage of the nontriggered switches. Resistors used for both charging and grounding (a.k.a. "keep alive" or "clamping") are of the simple copper-sulfate-solution-in-tygon-tubing type and are interconnected and supported by copper plumbing hardware. Connections between the capacitors and Marx column are made with flexible metal braid. Thus the entire Marx is easily modified or repaired. Stray capacitance between stages is deliberately kept to a minimum because (a) the $N = 4$ coupling assures breakdown of all the switches without the need for capacitive coupling, and (b) the authors hold to the notion that he who lives by stray capacitance dies by stray capacitance.

The Marx switching is performed in six Lucite tubes (hereinafter referred to as columns). Each column has four switches which consist of two hemispherical brass electrodes facing each other. The gap spacing is determined by external spacer blocks as shown in Fig. 5. Note that the gap spacing, and hence the breakdown voltage, can be easily adjusted by substitution of different thickness spacers. (Note also the electrodes are readily removed altogether.) This enables the Marx to be operated over a wide range of voltages while keeping the gas pressure in the column to within tolerable limits (e.g., less than 15 psig). The columns are hung from nylon straps from an overhead pipe and mounted at a slight incline. Each column has its own separate input and output tubing to allow for individual flushing with liquid freon for cleaning purposes. The contaminated freon is held in a recovery tank at the bottom of the Marx from where it can be drawn up for disposal.

The working gas in the column is ultra pure nitrogen, chosen for its cost, availability, purity, consistent composition, relatively benign effect on human life, and ability to agree with published breakdown curves. Regarding the last point, in Fig. 7 are shown actual breakdown curves for only one switch and the relevant calculated curve.[5] The agreement indicates that the individual switches are behaving as expected. In actual practice, when all 24 switches are connected, the breakdown voltage is some 10% lower, probably due to the statistical odds against obtaining twenty four identical gaps.

Each of the four gaps in the first column is triggered directly from an 80 kV pulse generator. Triggering is achieved with a single .080" dia Tungsten wire placed midway between the two electrodes and held at half the gap potential by two equal resistors. When the pin is driven negative by the pulse generator, the field between the electrodes is distorted and the gap breaks down. (Driving the pin negative produces free electrons to ensure rapid breakdown.) Two 2700 pf at 40 kV capacitors in series isolate the pulse generator from the Marx while the latter is charging, whereas winding the trigger cable in a coil prevents Marx transients from fouling the pulse generator.

Triggering the first four switches applies a four-fold overvoltage across the first gap of the second column. However, this is not necessarily sufficient to guarantee rapid breakdown. The needed free electrons are supplied by "passively triggering" the gap. This is accomplished with a balanced midplane pin, as in the first column, but instead of driving the pin with a pulse generator, it is driven by the output of the last stage of the first column. The remainder of the switches in the second column then breakdown by overvoltage, with the free electrons supplied by ultraviolet radiation from the first switch. This method is duplicated in the remaining four columns.

In order to facilitate very rapid jitter-free erection, the spacings between the electrodes of the first column are held within 10% of breakdown. However, the remaining gaps are all larger than this value by 25%, thus virtually eliminating any prefiring of the column.

The trigger pulse network is shown schematically in Fig. 8. The −80 kV pulse is obtained by charging a cable to +40 kV and shorting the opposite end with another midplane gap, which in turn is triggered by another charged cable shorted by a pressurized Trigatron switch, which in turn is triggered by a TM-11 30 kV trigger generator (which in turn is triggered by a series of delay generators, which in turn are triggered with a thumb on a button). The entire system has proven to be quite reliable, and the jitter, from the delay generator to erection of the Marx is less than ±20 nsec, with the major contribution due to the TM-11.

Accessibility in Marx was one of the design constraints. There is ample room to move in the rectangular noncoffin shaped tank, each column resistor or capacitor can be removed independently, and the trigger system is readily accessible. (Excess oil from one's person, which is usually the state of affairs after doing time in the tank, can be removed by total immersion for one half hour in a solution of People's brand musk oil bubble bath.)

BLUMLEIN

The Blumlein consists of three coaxial tubes, the outer one made of 304 stainless steel and the two inner ones made of aluminum. The inner and intermediate conductors are approximately 60" long, resulting in a round trip pulse length of 100 nsec.

The intermediate conductor is a 30" diameter aluminum tube, welded to a standard dished head and is cantilevered from the Marx/Blumlein Lucite diaphragm. (In TRITON the intermediate conductor is not cantilevered, but as it was found that the external support severly limits the charging voltage on the Blumlein, it was eliminated in POSEIDON.) The inner conductor is constructed in similar fashion, except the end is turned from a solid billet of aluminum to withstand the shock when the water switch fires. The inner conductor is cantilevered from the opposite diaphragm. To aid in support, appropriately placed vent holes make the conductor sufficiently buoyant to be just weightless when the line is filled with water. The entire Blumlein is filled with filtered, de-ionized (>7 Megohm-cm) water and is circulated after every four or five shots. Care must be taken to use similar metals or inert plastic in the water system, otherwise galvanic action will do some very interesting things to the aluminum surfaces. Before final assembly, all metal surfaces are rubbed with Scotch Brite pads, as this has been shown[6] to retard electrical breakdown in water.

The externally-adjustable self-break water switch is shown in Fig. 9. The intermediate-conductor electrode is a hardened shaft of stainless steel connected to the Marx by a flexible connection. Adjustment of the switch is effected with a right angle drive gearbox and a removeable keyed shaft. The stainless steel inner conductor electrode is polished and formed to just fit into a cavity in the inner conductor. A piece of closed cell neoprene behind the electrode helps to absorb the switch shock. Correct adjustment of the water switch is realized when the switch breaks at peak charge on the Blumlein, as determined by the Blumlein voltage monitor waveform.

There are three 3" diameter ports around the outer conductor. One is for a voltage monitor, the other two have corresponding holes in the intermediate conductor to allow a direct visual examination

of the switch gap or any strange happenings therein. A large 12" diameter vent on top of the outer conductor also helps relieve the water switch shock.

The prepulse inductor is a simple .64 cm diameter copper rod bent into a spiral and attached between the inner conductor and outer conductor in the oil filled prepulse switch section. The object of the game is to adjust the inductance so the impedance is small on the Blumlein charging time scale (thus ensuring the inner conductor is always near ground potential), but large on the beam pulse time scale (thus minimizing the energy shunted away from the diode). This balancing act was assisted with a simple circuit model of the Marx charging the Blumlein.[7] In Fig. 10, the predicted voltage waveforms on the Blumlein monitor (between intermediate and outer conductor), on the inner conductor, and across the water switch, are shown for the case of too large a prepulse inductor and one near optimum. Optimum is signified by a simultaneous maximum in the Blumlein and water switch waveforms and a zero on the inner conductor. (The voltage varies on the inner conductor because it is capacitively coupled to the intermediate conductor as it is being charged.) Note that an improper prepulse inductor can be easily discerned by proper interpretation of the Blumlein voltage waveform.

PREPULSE SWITCH

The purpose of the prepulse switch is to prevent the relatively small variations in the inner conductor potential from prematurely shorting out the diode. The prepulse switch is a point-to-plane oil filled gap (see Fig. 11), the single electrode being mounted on a square cut thread to facilitate adjustment and prevent unintentional movement. The oil is circulated between each shot through a filter in order to ensure reproducibility. While the single electrode arrangement is somewhat inductive, and thus retarding the diode voltage risetime, it was felt that this was a relatively low price to pay to avoid the headache of getting a multichannel switch to function properly. Ports allow for visual and diagnostic access to the switch.

As with the prepulse inductor and water switch, the exact setting of the prepulse switch can be determined by a careful study of the Blumlein monitor. Waveforms are shown stylistically in Figs. 12, 13 and 14 for various settings of the prepulse gap. For a properly set gap (Fig. 12) the Blumlein voltage reaches a peak, then abruptly drops through zero on a time scale on the order of the beam pulse width. If the switch gap is too large (Fig. 13), the energy is not switched to the diode immediately after the water switch breaks, but instead is shunted through the prepulse inductor to ground. This is indicated as a normal rise but abnormally slow fall in the Blumlein voltage. (The fall need not be monotonic in this case; indeed if the prepulse switch finally decides to conduct during this phase the fall will be accompanied with some type of bump, step or other seemingly unintelligible discontinuity.) On the other hand (Fig. 14) if the switch gap is too small (or laziness has prevented circulation of the oil), the switch fires when there is still voltage on the intermediate conductor, which in turn appears on the outer conductor and consequently as a pulse on top of the main Blumlein monitor waveform.

DIODE

The POSEIDON diode, shown schematically in Fig. 11, uses a plane Lucite diaphragm and a field emission cathode. The planar diode was chosen over its main competitor, the stack ring diode because it is: (1) easier to clean, (2) less likely to leak, (3) easier to repair, (4) stronger, (5) compatible with available NRL simulation codes, and (6) amenable to major modifications. (In fact, the design has actually allowed the placement of a 10 kg magnetic field coil in the cathode, the power to the coil being brought in through an isolation inductor in the oil section.) The main drawback in this design was the procurement of a large enough piece of Lucite to make the diaphragm; a problem which was solved by gluing together two pieces as shown in Fig. 15.

The electrical design of the diode was conceived along the guidelines recommended by J. D. Shipman[8]:

(1) Electric field perpendicular to interface: According to Shipman, radial flashover across the Lucite interface is suppressed if the electric field lines are perpendicular to the interface, and enhanced if they are parallel. As a general rule, a minimum angle of 60° should be observed. This field shaping is usually achieved by carving a compound curved cone out of the back of the Lucite diaphragm and inserting a conductor of identical shape into the resulting cavity. In addition to the obvious disadvantage of cost, such a method also structurally weakens the Lucite, so it is more likely to break and cost even more. In POSEIDON the same effect is achieved by placing a large pizza-pan shaped electrode immediately behind the Lucite (i.e., in the oil section) and an appropriately shaped aluminum dome in the vacuum region.

(2) Shielded triple point: Shipman suggests that the region where vacuum, metal and Lucite meet be well away from any high field stresses, as this is where the dastardly flashover producing streamers are born. This is achieved by the now commonly accepted practice of carving a radial step in the aluminum dome where it intersects the interface.

(3) Prevent ultraviolet irradiation of interface: The u.v. from the anode cathode gap or any sparking joints can also trigger interface flashover. To this end; a large Lucite disk is placed around the cathode, (in order to shield the interface from the anode-cathode gap); the cathode spacer rings (used to adjust the diode gap) are all located inside the dome; and the connection in the current return on the door flange is made with beryllium copper fingers inside a protective housing.

An electrostatic field plot of POSEIDON's diode appears in Fig. 16. This plot was made with a code originally developed by J. D. Shipman.

Typically the diode can go up to 20 shots without maintenance, which usually consists of cleaning all nonemitting surfaces and recoating them with a mixture of 2 parts Dow Corning 704 fluid and one part trichlorethylene. This mixture has been found[9] to more evenly distribute the Dow Corning fluid than if it were just applied directly.

DIAGNOSTICS

The voltage in the Blumlein and prepulse section are monitored using simple capacitive dividers (Fig. 17). These dividers are operated in the differential mode to allow a wide frequency response and to permit large, noise-free signals to be transmitted back to the screen room.

The voltage in the diode is measured with a resistive copper sulfate voltage divider in the oil prepulse section (Fig. 18). As designed by A. W. DeSilva, the cross section of the divider varies with radius in order to keep the radial electric field variation in the divider the same as in the surrounding oil. The divider was filled with a weak copper sulfate solution as it was found that at more concentrated solutions the division ratio was not constant with voltage.

The two capacitive voltage monitors were calibrated *in situ* by discharging an 80 kV pulse from one of the Marx triggers across the appropriate set of conductors. Calibration was based on a Tektronix 1000X high frequency probe located in the same position. (While the probe is rated at only 40 kV, it can be abused by a factor of two, at least, if it is totally immersed in water or oil. Such procedures probably invalidate the warranty, however.)

Diode current is measured with a simple one turn loop situated in the diode door in such a position to measure the azimuthal field from the current. The loop is calibrated against a Rogowski coil in order to confirm there were no azimuthal variations in the current path. The coil is in turn calibrated against a known current shunt. Similar loops were also placed in the prepulse section, anode cathode gap and next to the interface in order to check if any radial loss of current occurred. These probes however are not routinely employed.

As the diode voltage is measured in the prepulse section, it is not a direct measure of the voltage in the diode gap because of the inductance of the cathode. This effect is compensated for electrically by using a second one-turn loop in the diode door to look at dI/dt and electrically subtracting this from the diode voltage. Adjusting this signal so that V − dI/dt is zero when the diode is shorted (i.e., zero volts in the gap) gives the true diode potential when the diode fires normally.

In Fig. 19, typical diode voltage and current traces, are shown for a charging voltage of 35 kV. In Fig. 20, the Blumlein voltage waveform is shown for the same shot.

ACKNOWLEDGMENTS

The authors are greatly indebted for helpful discussions with J. D. Burton, A. W. DeSilva, K. A. Gerber, J. C. Martin, A. E. Robson, J. D. Shipman, and D. N. Spector; for the excellent engineering drawings of M. O. Sy and J. Chow; and the invaluable technical assistance of D. R. Evenson and W. D. Webster.

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2. J.D. Sethian, Naval Research Laboratory Memorandum Report No. 3785.

3. J.D. Sethian, K.A. Gerber, D.N. Spector and A.E. Robson, Proceedings of the 4th Int. Topical Conference on High Power Electron and Ion Beam Research and Technology Palaiseau, France, June 29-July 3, 1981, p. 549.

4. These anode foil changers, to be described in a later Memorandum report, operate on the same principle as an air lock. They allow a fresh anode foil to be placed in position without destroying the system vacuum.

5. J.D. Cobine, Gaseous Conductors, Dover Press, N.Y., (1958), p.174.

6. J.C. Martin, private communication.

7. A.E. Robson, private communication.

8. J.D. Shipman, private communication.

9. J.C. Martin, private communication. The original suggestion was to use a mixture of 704 fluid and methylethyl ketone, but not having any of the latter on hand led to trying trichlorethylene which seemed to work fine.

Table I

Marx	
Tank capacity	8000 gallons
No. of stages	24
Capacitance per state	$2x\ .5\ \mu f$ at 100 kV
Coupling	N = 4
Erected capacitance	41.67 nF
Erected inductance	14.7 μH
Working gas in switches	N_2
Blumlein (water dielectric)	
Pulse length	100 nsec
Capacitance inter-outer	15.20 nF
Capacitance inner-inter	10.00 nF
Total impedance	8.8 ohms
Switch	Single channel water insulated
Prepulse inducter	4 μH
Prepulse switch	Single channel oil insulated
Performance (40 kV charge)	
Diode volts	800 kV
Diode current	100 kA
Pulse length	100 nsec
Jitter (total)	$\pm$40 nsec

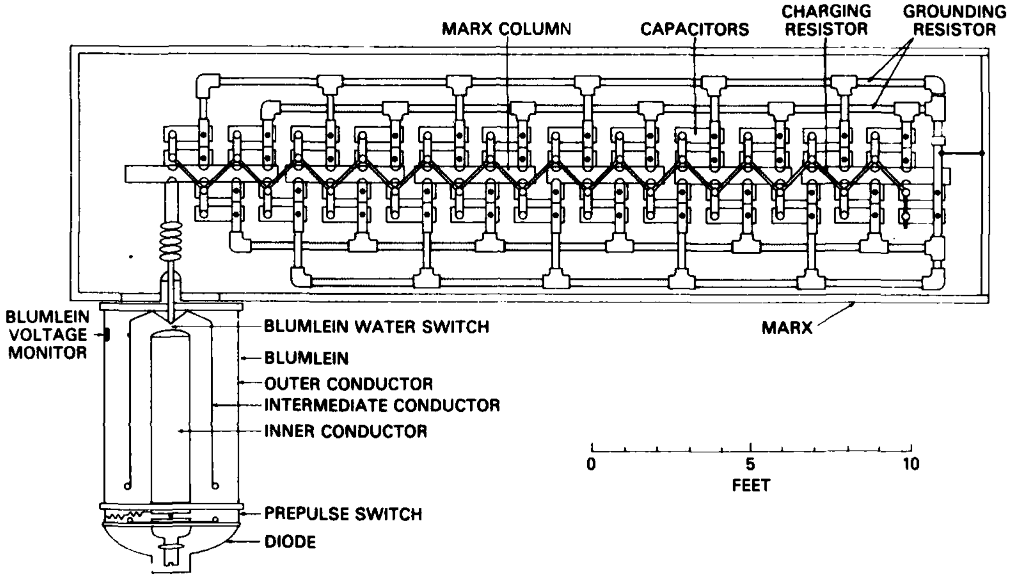


Fig. 1 — Overall drawing of POSEIDON

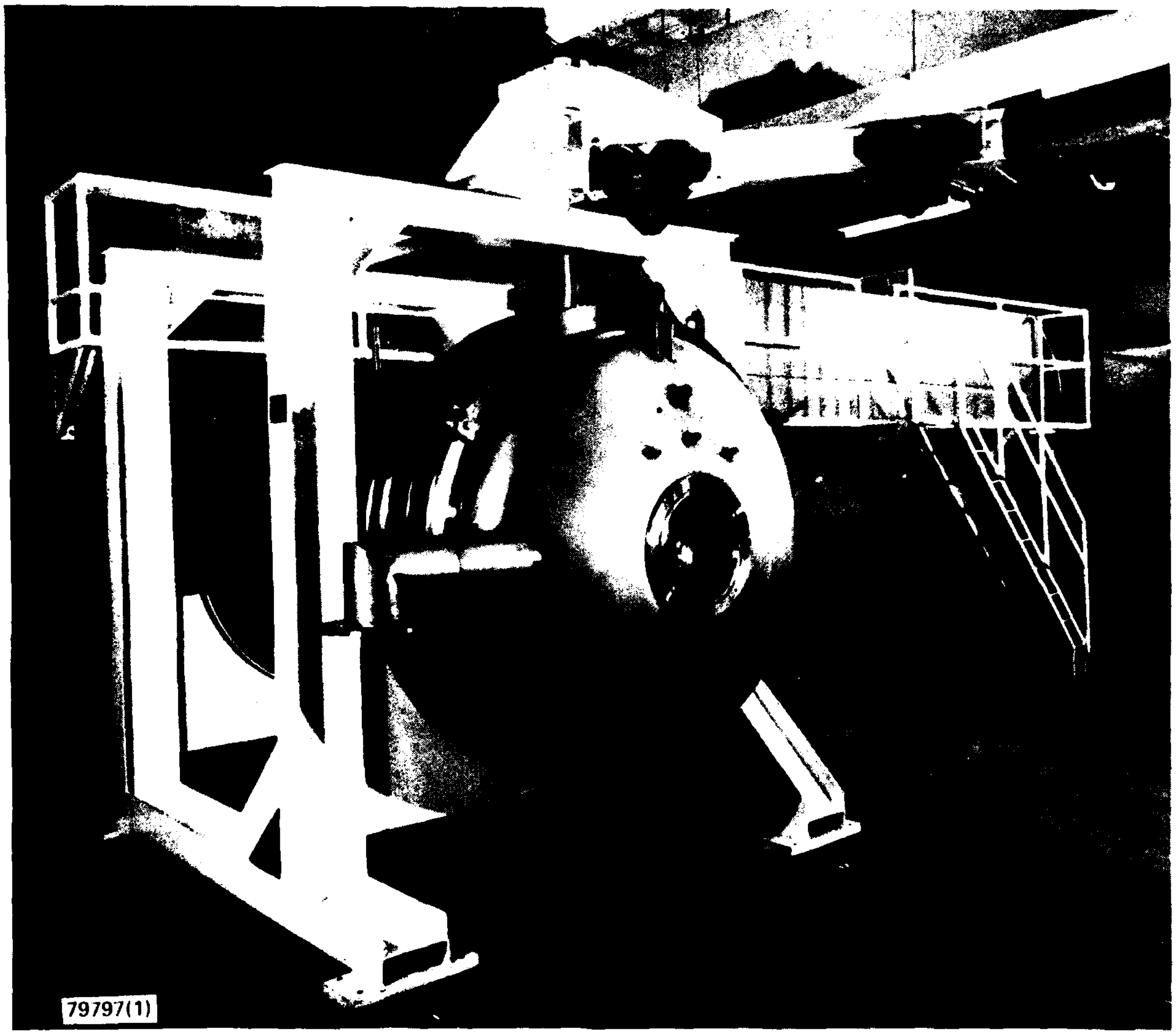


Fig. 2 — Photograph of POSEIDON

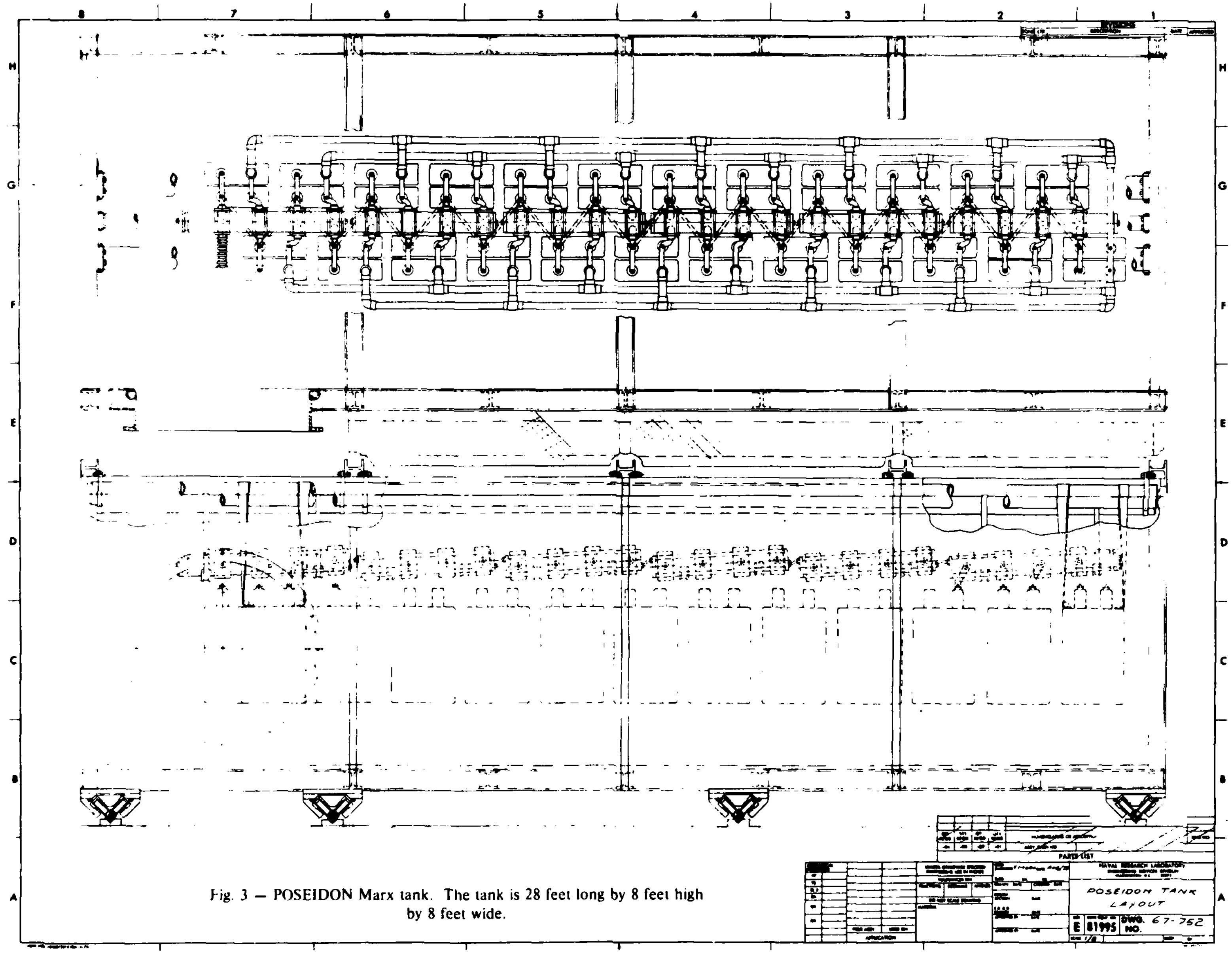


Fig. 3 — POSEIDON Marx tank. The tank is 28 feet long by 8 feet high by 8 feet wide.

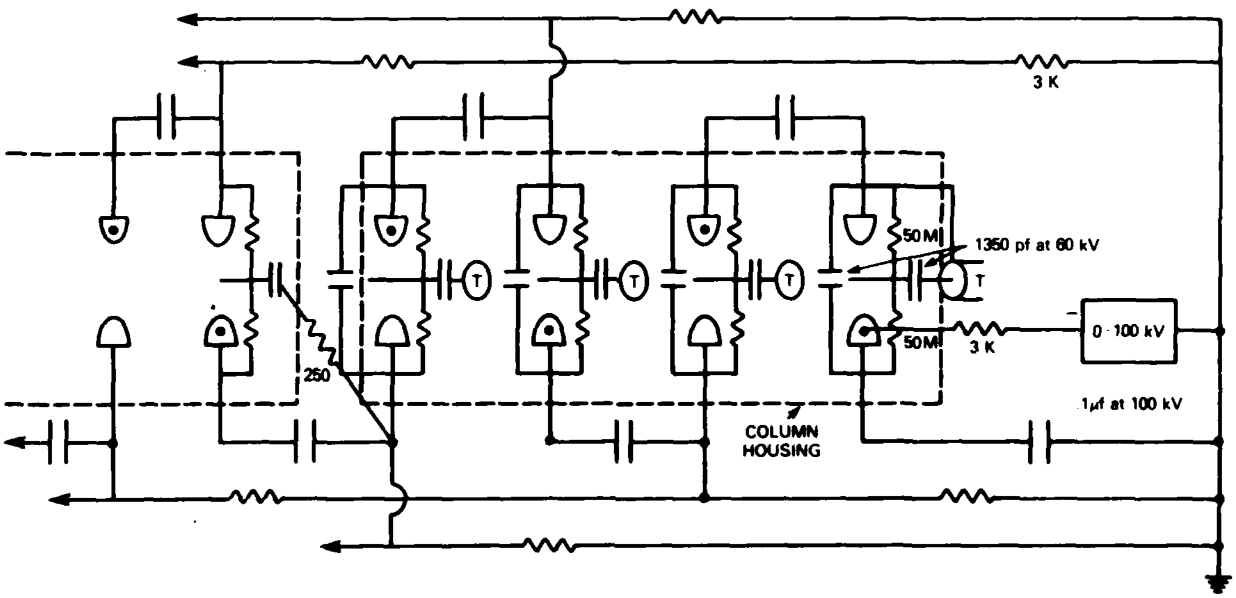


Fig. 4 — Marx circuit and connections. Only the first six stages are shown. The dots are connected with 3kΩ resistors for charging (eliminated in the drawing for clarity). The "T" denotes connection to the trigger generator.

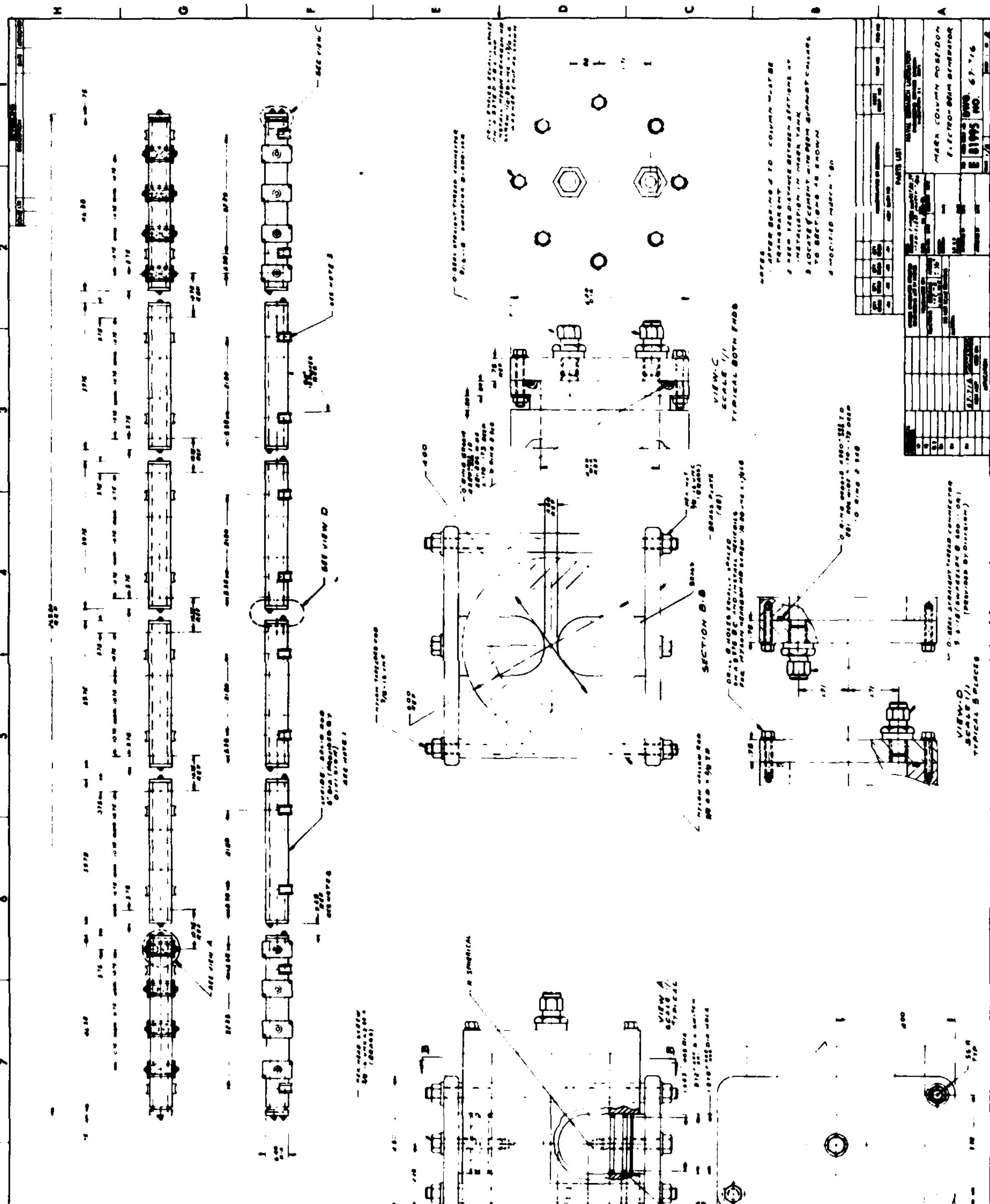


Fig. 5 — Mechanical drawing of the Marx columns

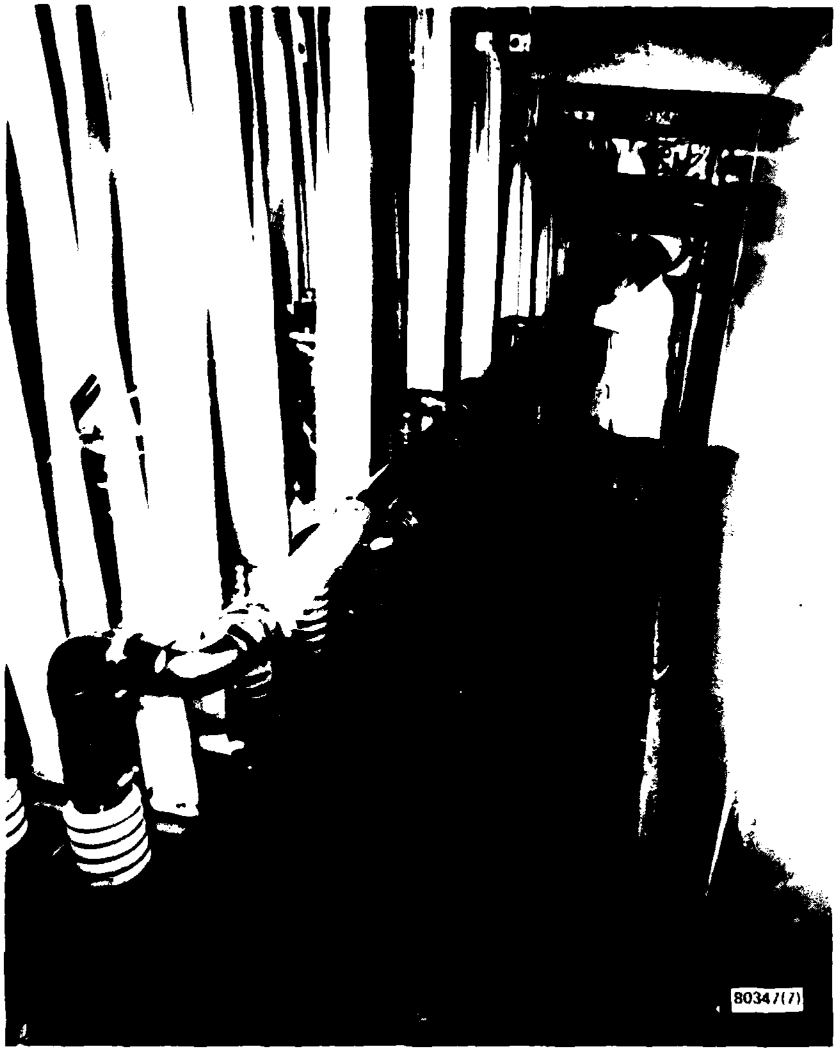


Fig. 6 — Photo of Marx

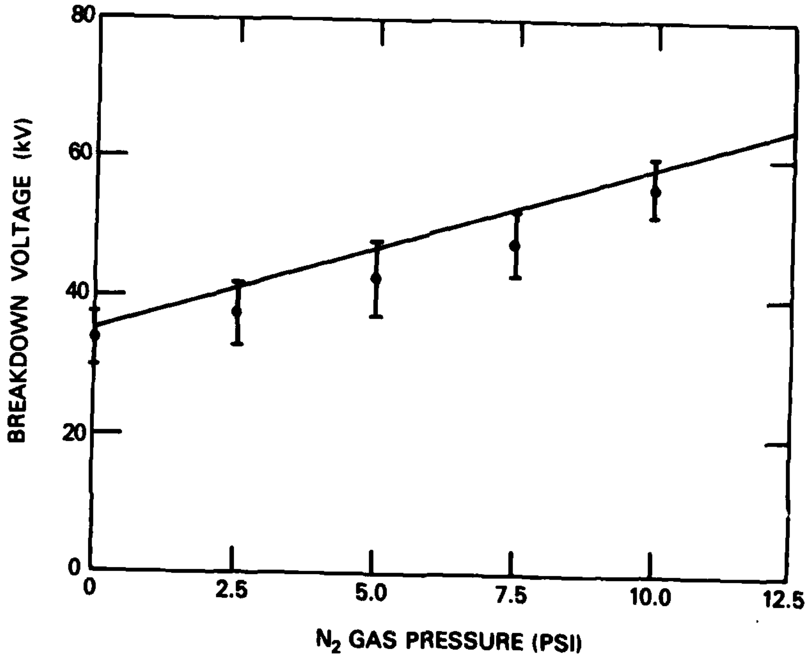


Fig. 7 — Theoretical[5] and actual breakdown curves for a single switch

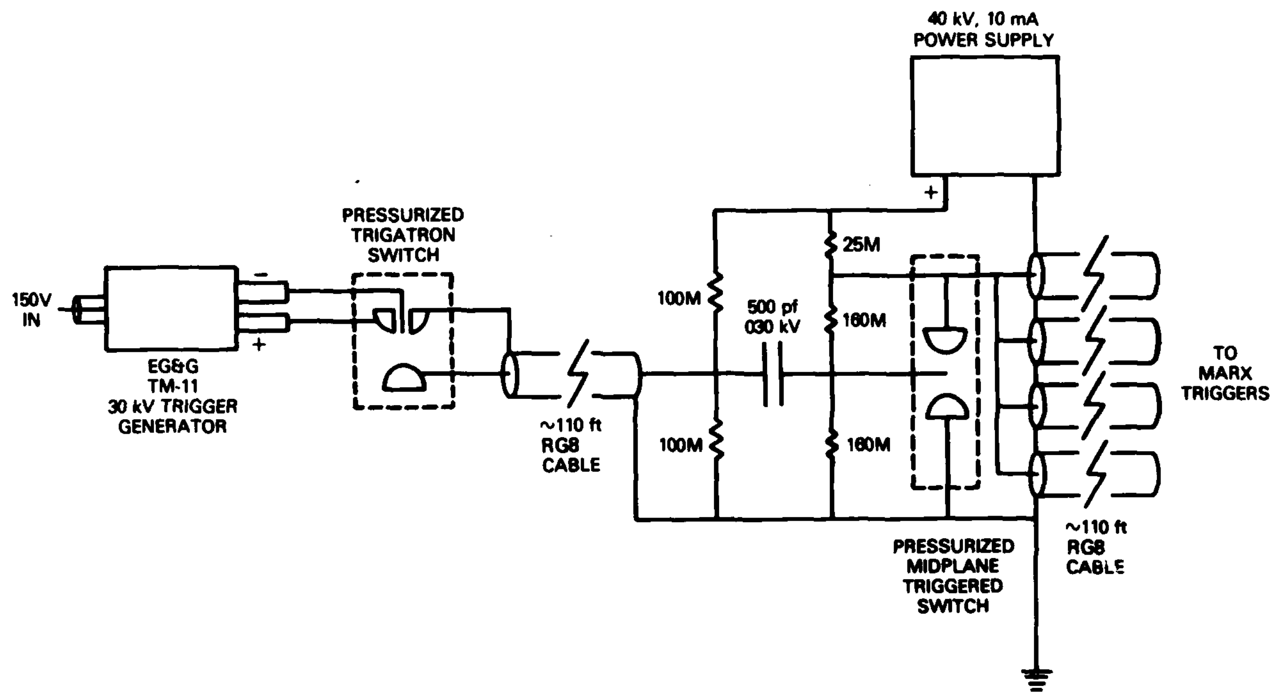


Fig. 8 — Marx trigger generator circuit

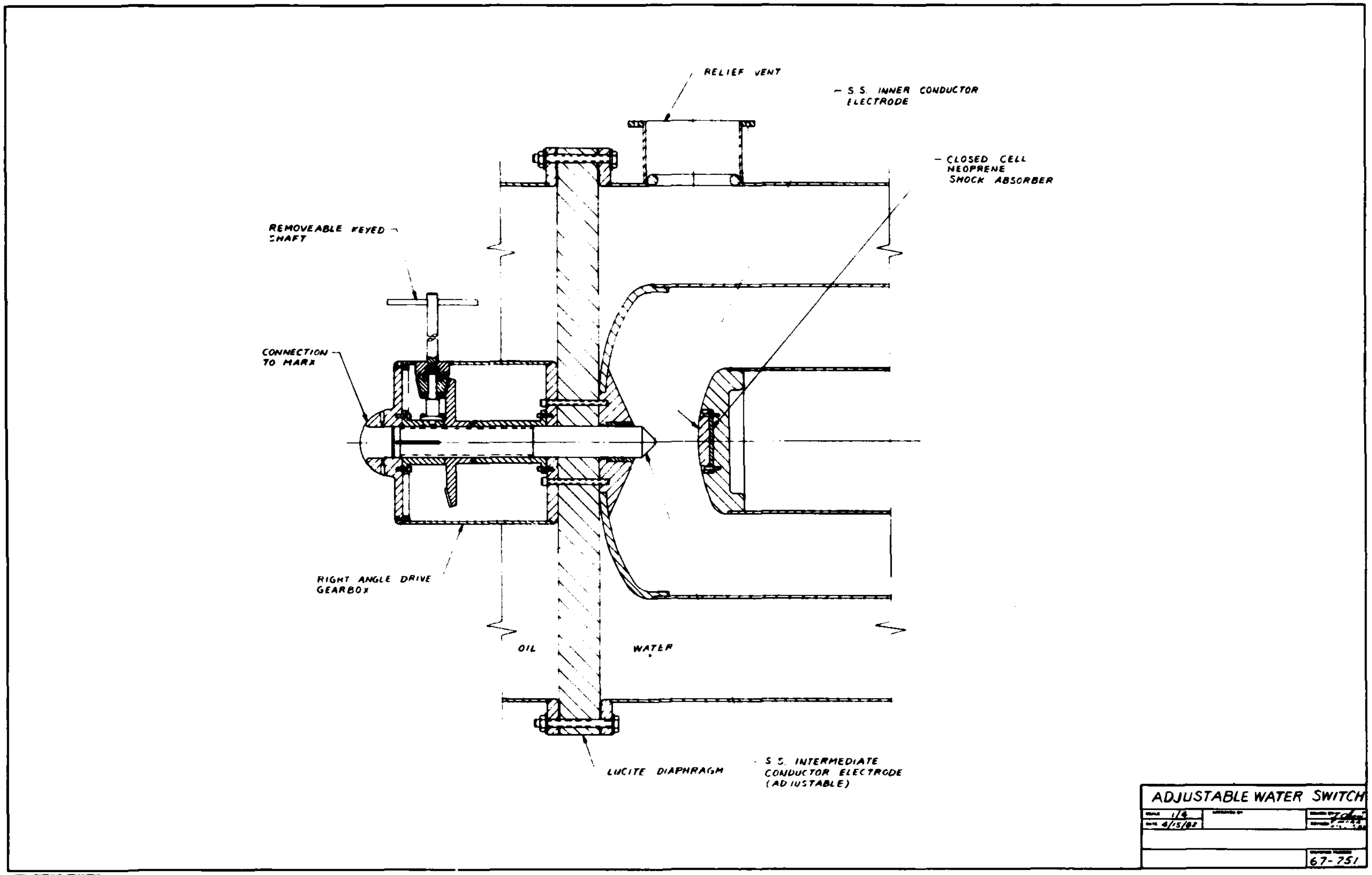


Fig. 9 — Drawing of adjustable water switch

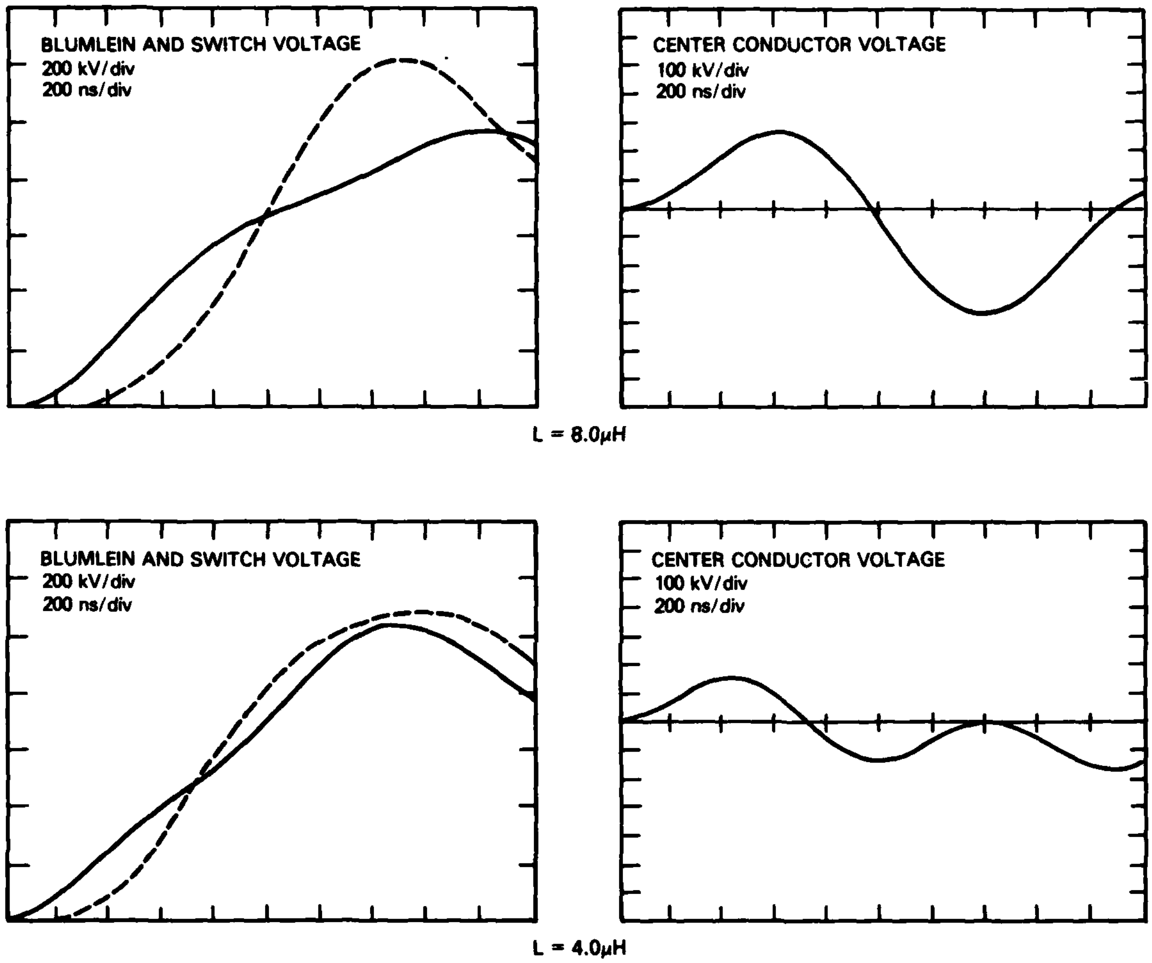


Fig. 10 — Predicted Blumlein voltage monitor (solid line), voltage across the water switch (dotted line), and inner conductor voltages for two different prepulse inductors. Upper: Inductor ~8.0 μH (too large); Lower: Inductor ~4.0 μH (near optimum). The Blumlein voltage waveforms were verified experimentally.

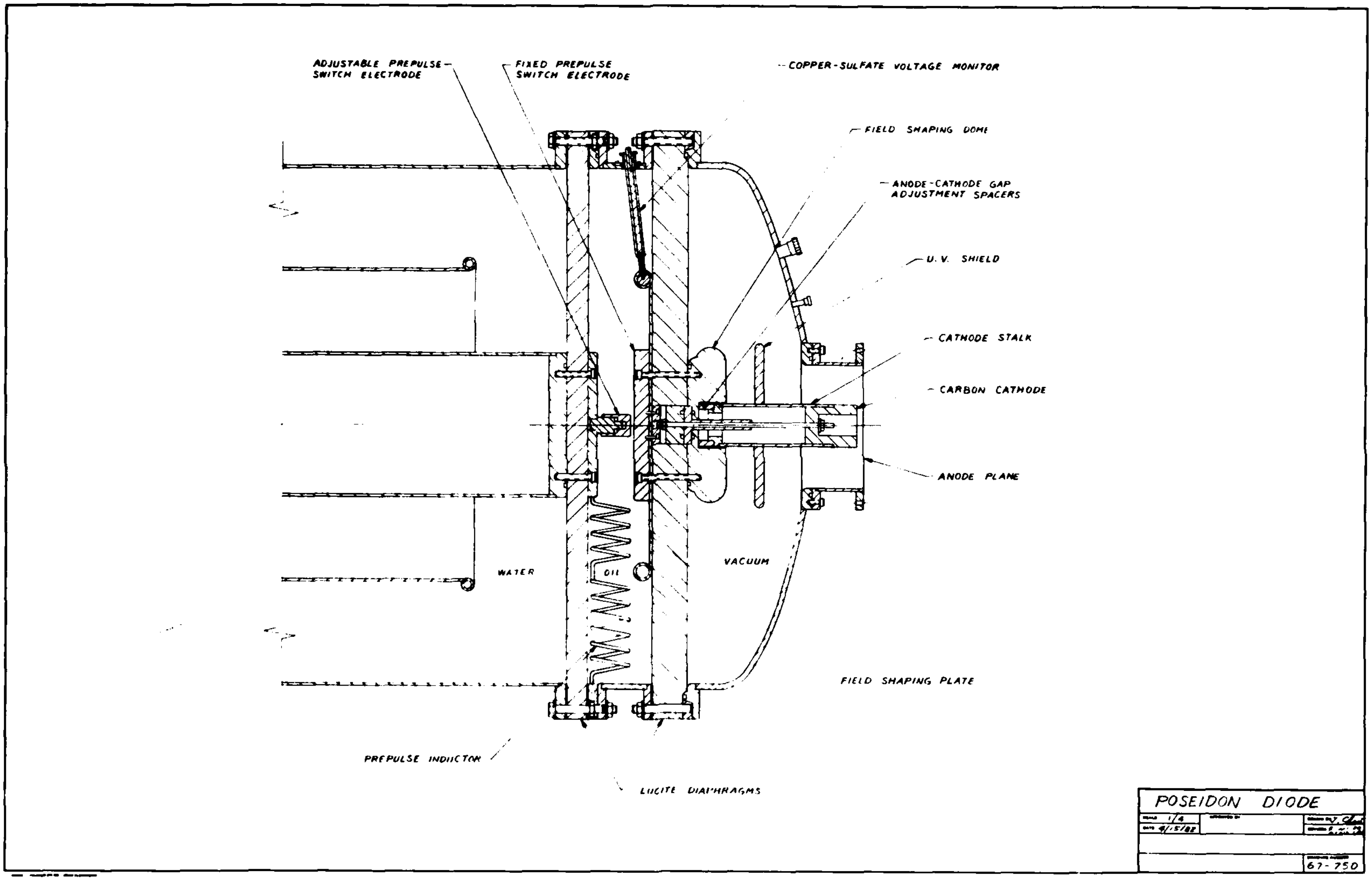


Fig. 11 — Drawing of prepulse switch and diode

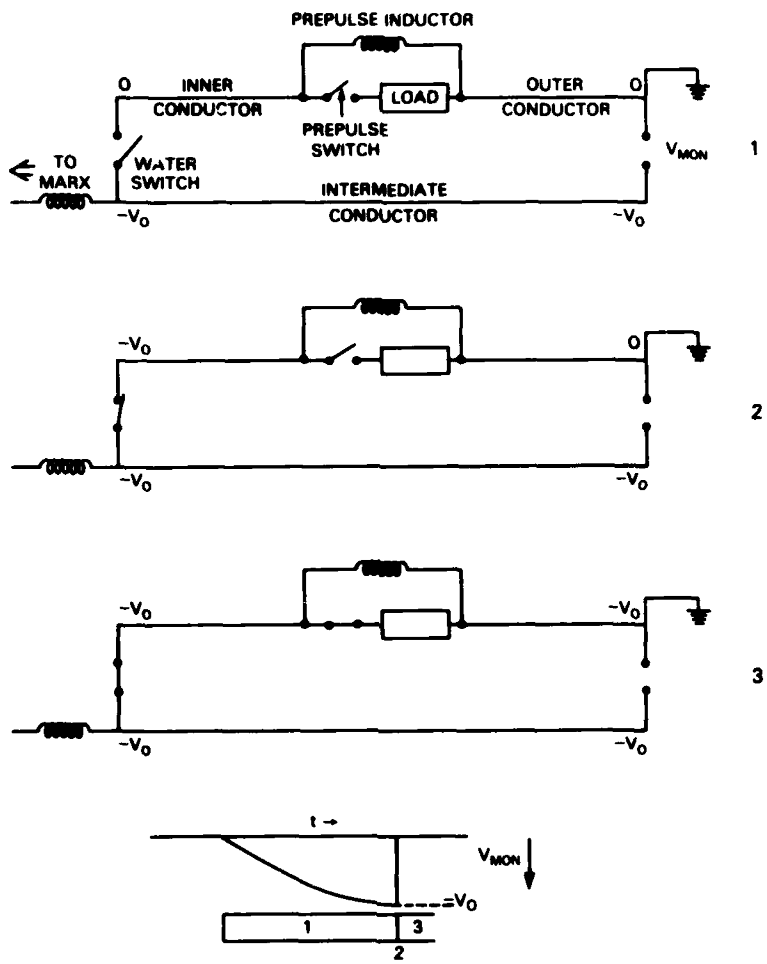


Fig. 12 — Case I — Proper prepulse gap (switch closes at $V_{intermediate} = V_0$, $V_{inner} = 0$). (Blumlein is shown unfolded as a strip line.) (1) Marx charges intermediate conductor to $-V_0$; (2) Water switch closes, driving inner conductor to $-V_0$; (3) Prepulse switch closes, putting $-V_0$ across load. Since outer conductor is now as same potential as intermediate, Blumlein monitor drops to zero.

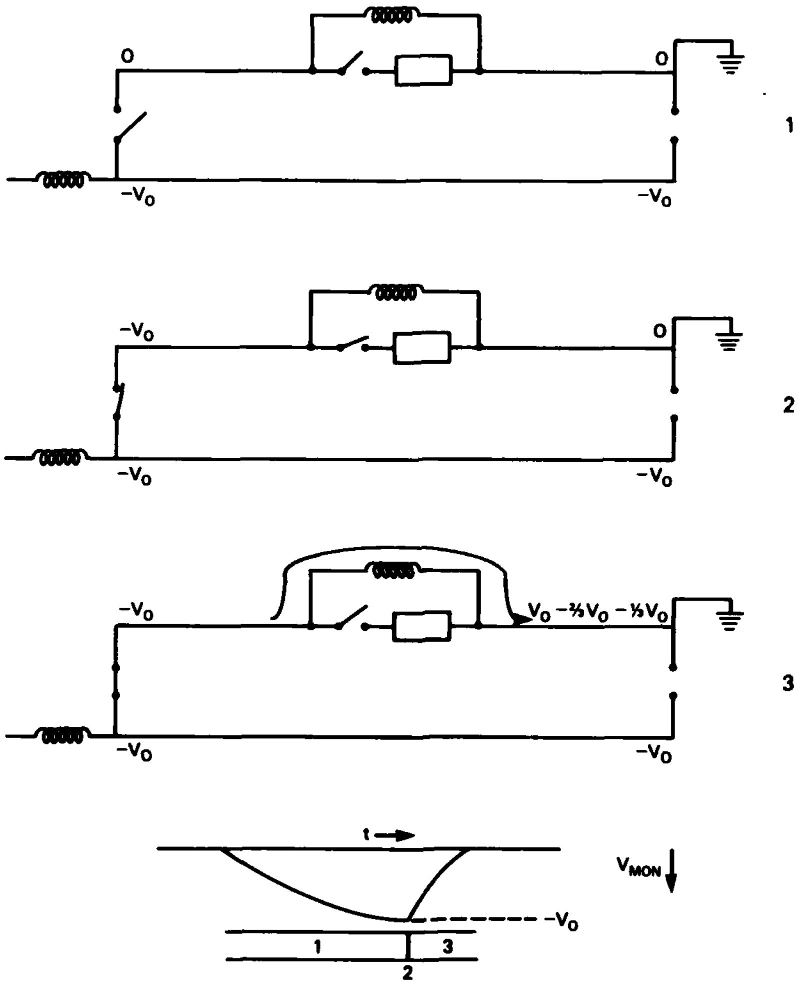


Fig. 13 — Case II — Prepulse gap too large (switch closes late). (1) Marx charges intermediate conductor to $-V_0$; (2) Water switch closes, driving inner conductor to $-V_0$; (3) Since only connection to outer conductor is through prepulse inductor, voltage rises slowly, resulting in slow fall in monitor (Note: if prepulse switch closes during this period steps will appear in fall).

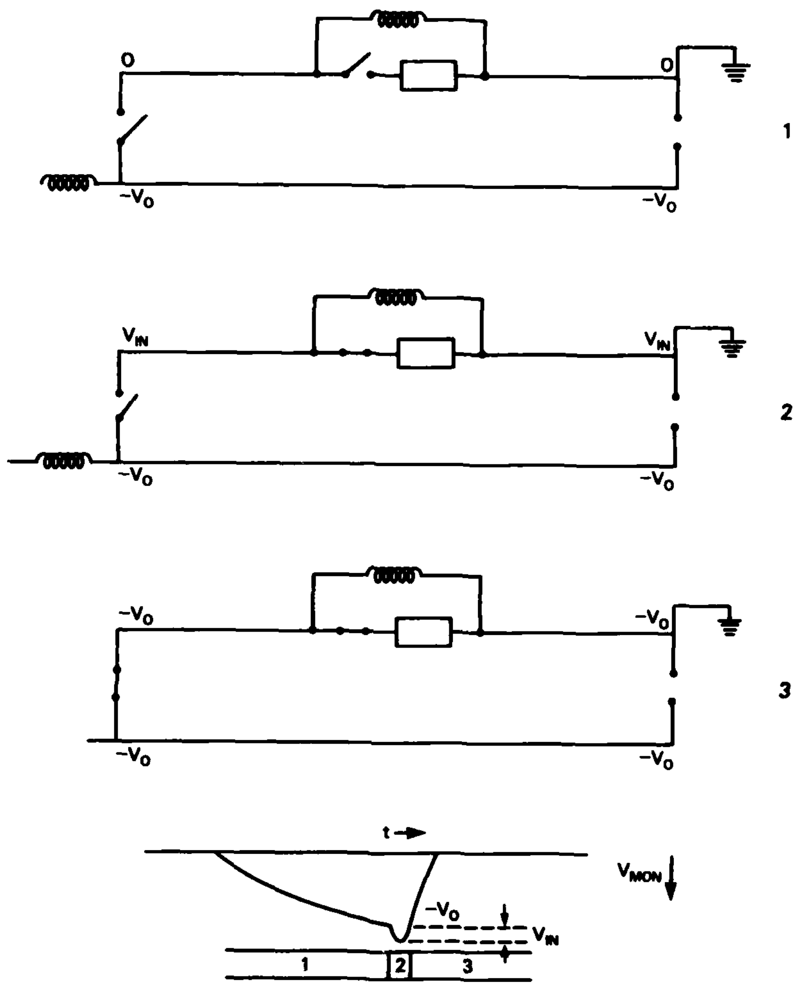


Fig. 14 — Case III — Prepulse gap too small (switch closes early, when $V_{inner} \neq 0$). (1) Marx charges intermediate conductor to $-V_0$; (2) Prepulse switch closes. Since voltage on the inner conductor is at some nonzero positive value, V_{in} (see Fig. 10), the voltage on outer conductor rises by V_{in}, thus raising the monitor voltage; (3) Water switch closes, bringing $V_{outer} = -V_0$, as in case I.

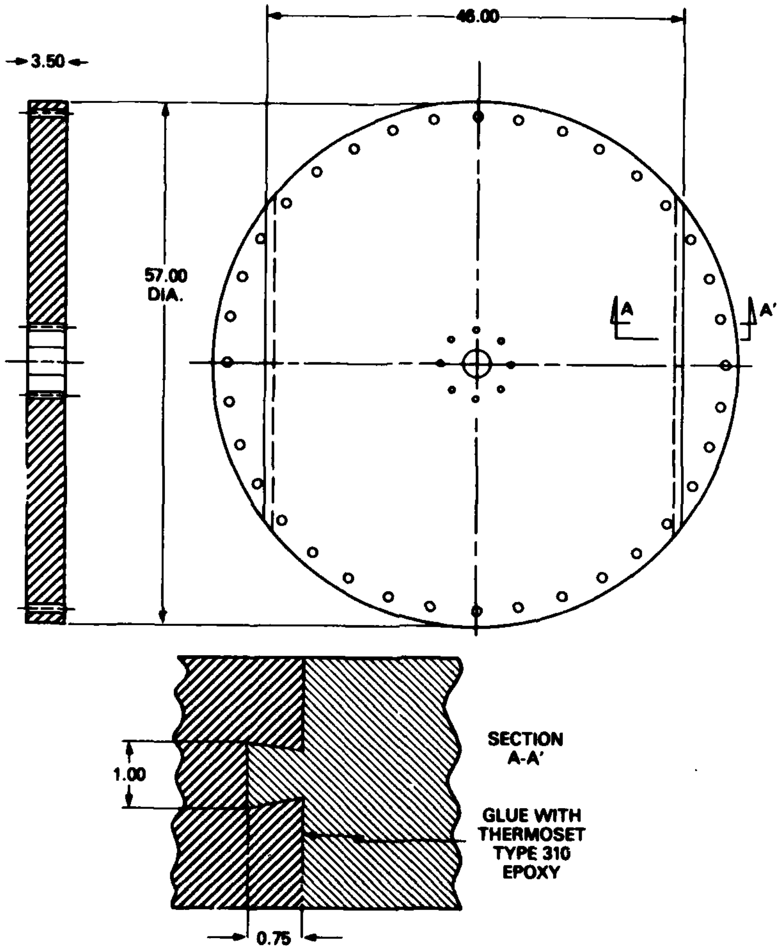


Fig. 15 — Assembly of 57" diameter 4" thick Lucite diaphragm for diode from 72" × 48" Lucite stock

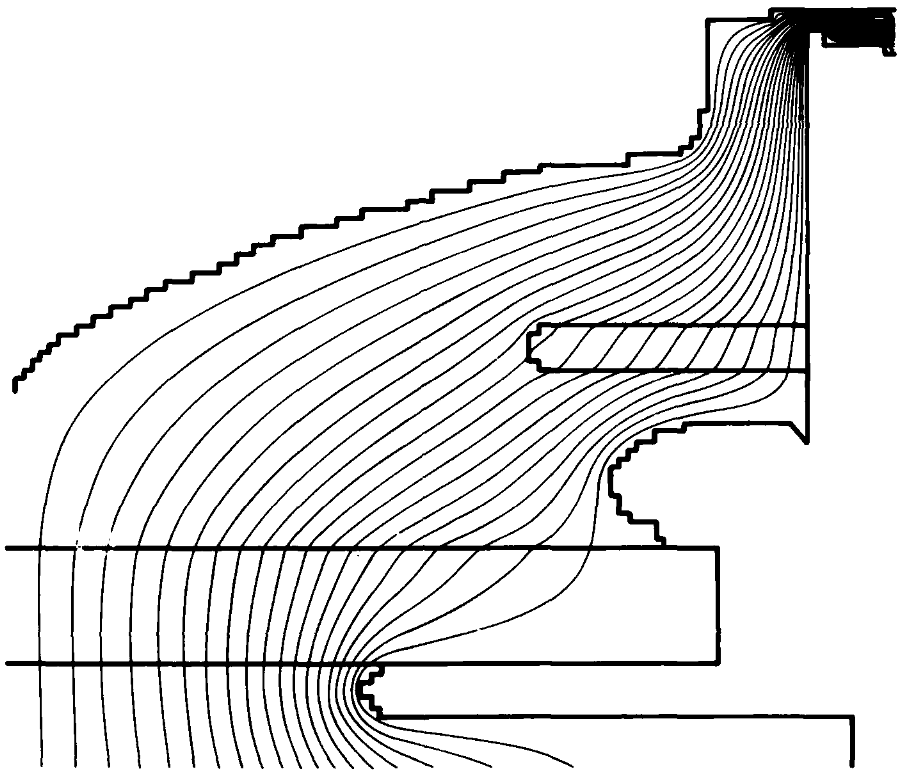
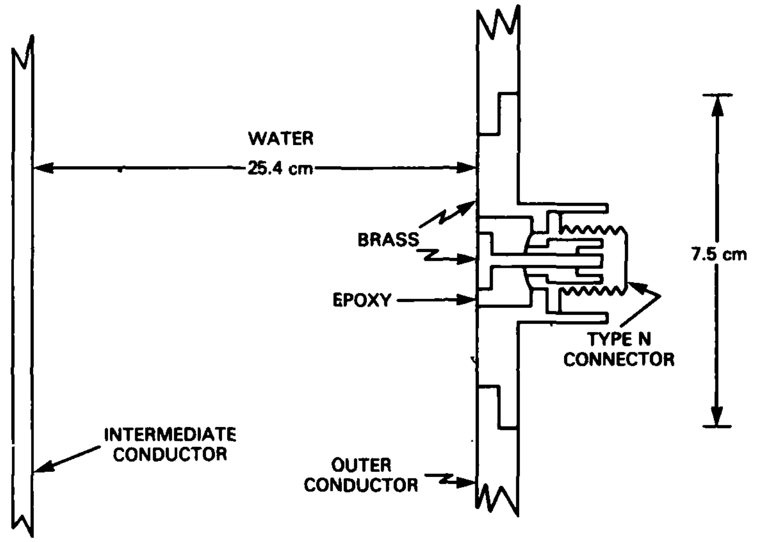
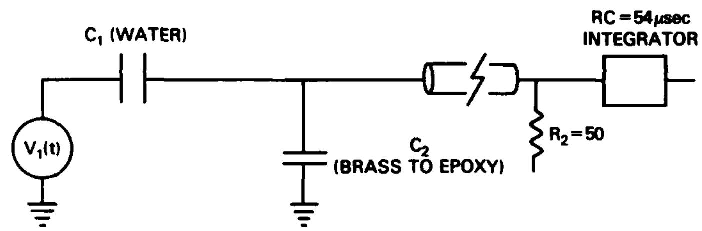


Fig. 16 — Field plot of Poseidon diode. Each contour corresponds to a 5% variation in potential.



(a)



(b)

Fig. 17 — Capacitive voltage divider and equivalent circuit

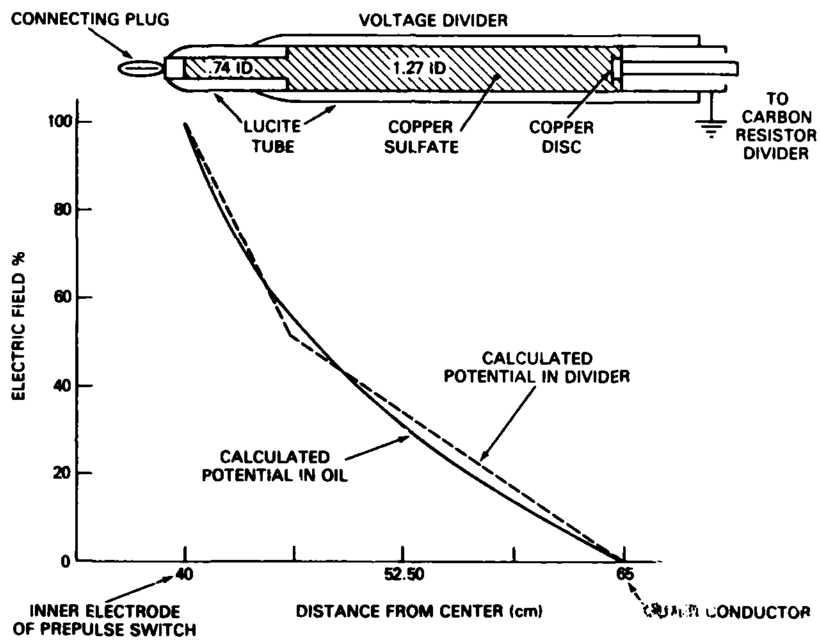


Fig. 18 — Diode voltage monitor

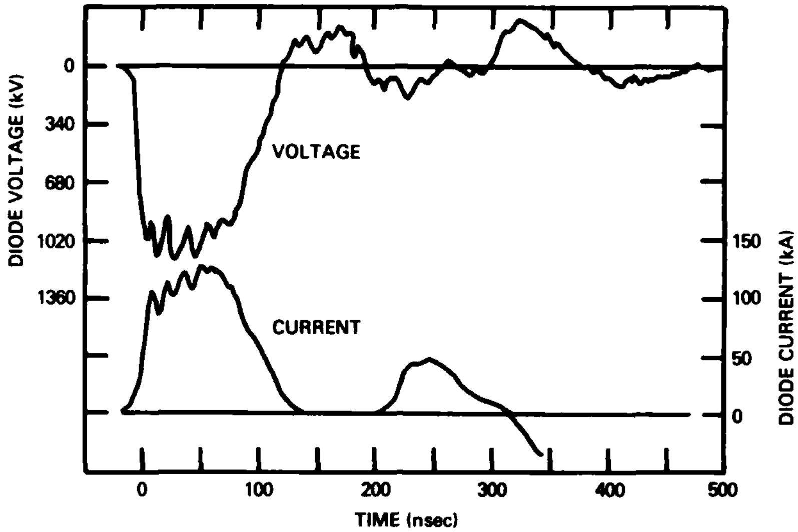


Fig. 19 — Diode voltage and Diode current waveforms

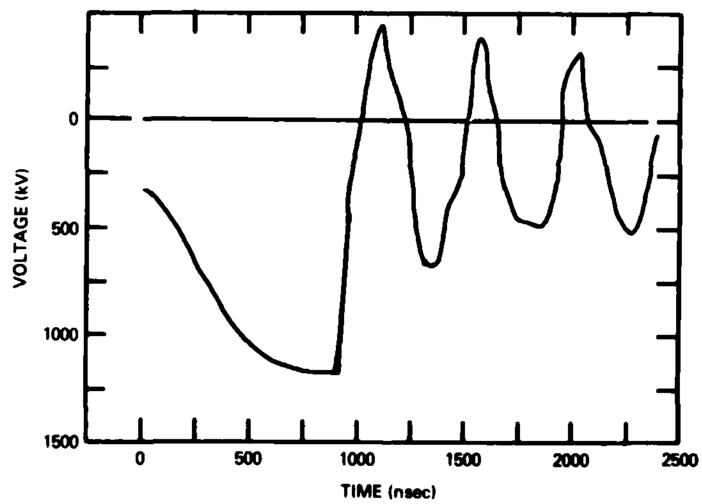


Fig. 20 — Blumlein waveform corresponding to Fig. 19. Note that over 67% of the Blumlein energy is switched out of the diode.